

Research Article

The Effects of Open Innovation Platform Knowledge Strategies on Participants: Evolutionary Game Research

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Based on previous research on open innovation and appropriability strategies, using knowledge production functions and evolutionary game methods, this paper describes the process of dynamic cooperation between open innovation platforms and their participants. This paper specifically analyzes the influence of open innovation platform's knowledge appropriability/knowledge sharing strategies, as well as participants' exit/nonexit strategy, on the cooperative relationship. Through simulation analysis, this paper draws the following conclusions: first, the knowledge appropriability strategy of the open innovation platform and the participant's nonexit strategy is an important strategic point of the cooperation between open innovation platforms and participants; second, the amount of knowledge production affects the strategic choices of open innovation platforms, while the knowledge increment affects the strategic choices of participants; third, the appreciation coefficient of complementary assets determines the direction of evolution of the cooperation process.

1. Introduction

Innovation profitability is affected by openness and sustainability [1–3]. An open innovation platform must have an effective cooperation mechanism that allows free entry, as well as deeper connections in various links based on knowledge, human resources, and other factors to maintain openness. Based on the classic theory “profiting from innovation (PFI),” appropriability allows enterprises to benefit from innovation, thereby avoiding the dilemma of the innovation paradox [2], which entails to process by which enterprises make strategic choices between openness and appropriability in the game of open innovation.

The appropriability strategy may be formal or informal depending on the ownership of the intellectual property [4, 5]. Proper coordination of openness- and appropriability-based profit in an open innovation platform can guarantee long-term, practical open innovation. Kyläheiko asserted that appropriability is a key issue for relational

companies to obtain profits from innovative activities [6]. The effectiveness of appropriability for corporate competition strategies, intellectual property protection, and benefits is obvious, although different views still exist [7, 8].

The early research in this field is characterized by a focus on the behaviors associated with unilateral acts of cooperation. Miotti and Sachwald [9], for example, found that enterprises are open to customer participants within the value chain. Su et al. [10] analyzed the upstream participants in innovation activities based on the industrial chain. Pihlajamaa et al. [11] discussed whether participant-led innovation can substitute internal research and development (R&D). Legenvre and Gualandris [12] found that a small number of enterprises with excellent performance expand the scope of their cooperation across participants at their secondary and tertiary levels.

The recent literature shows that research trends regarding open innovation have evolved toward the governance of open innovation platforms and productively

exerting appropriability strategies [11]. Zobel et al. [13] investigated how to integrate formal and informal appropriability mechanisms for collaborative ideation. Miozzo et al. [14] found a significant positive association between the innovation collaboration and formal appropriability mechanisms. Holgersson et al. [15] extended and nuanced the debate on intellectual property strategy, appropriation, and open innovation in dynamic and systemic innovation contexts. Gama [16] identified which appropriability mechanisms are pertinent during each phase of collaborative ideation and contributed to the discussion regarding the best method for integrating appropriability mechanisms for safe collaborative ideation.

However, the process of weighing the pros and cons of open innovation and appropriability as two parallel strategies of enterprises has not been paid sufficient attention in the literature.

Based on the above research review, this article will make improvements in the following aspects. First, the asymmetric evolutionary game model is used to study the relationship between the open innovation platform and the participants; second, the knowledge appropriability strategy is described under the open innovation platform strategies for the first time; third, the appreciation coefficient of complementary assets is used as a key variable of the knowledge production function.

2. Research Methodology

Since the relationship between open innovation platforms and their participants is ever changing and complex, the application of more systematic, dynamic and advanced methods is needed in order to describe the process of cooperation between open innovation platforms and their participants. The complex network method is a dynamic technique that can be used to describe complex social relationships [17, 18] and social cooperation networks [19] and has been applied to determining the structural characteristics of knowledge in the field of innovative cooperation analysis [20].

It is worth mentioning that the evolutionary game method is also suitable for this topic. It can not only construct dynamic relationships to describe complex problems but can also better solve the dynamic strategic problems of both parties. The evolutionary game method is increasingly being used to portray technology innovation [21], the path of evolution of the knowledge sharing strategy [22], and the cooperative strategy in open innovation [23], but it has not yet been applied to describing the mechanisms of openness and appropriability in innovation cooperation (e.g., system stability, profitable operation, and participant withdrawal behavior).

This paper was conducted in an effort to fill these gaps. Based on the applicability of the evolutionary game method, an asymmetric strategy evolutionary game between open innovation platforms and their participants was established based on the different positions of both parties [24, 25]. The semiopen innovation model was selected based on previous work by Tie [26].

3. Research Model

The effects of an open innovation platform's used knowledge strategy on the stability of the evolution of participant cooperation and withdrawal were investigated, with special focus on the knowledge increment and the complementary resources of open innovation. The differences in system evolution brought about by the open innovation platform's knowledge strategy, and participant withdrawal were analyzed under the asymmetric platform-participant strategy as well.

3.1. Research Hypothesis. Romer proposed a function based on the characteristics of knowledge production [27]: $Y = \delta HK$, where Y is the newly produced knowledge, H is the human capital input of the R&D activities, K is the knowledge stock required for producing the new knowledge, and δ is the productivity parameter of the R&D department, and $0 < \delta < 1$, $H > 0$, $K > 0$.

The open innovation process is full of knowledge creation [28], and Zhang et al. argued that cooperation innovation is a knowledge-creation behavior and that knowledge production and creation are based on its own capacity and the common knowledge of other groups [29]. Cooperative innovation brings about knowledge growth, which can be defined as a "knowledge increment" produced based on an original stock of knowledge [26]. Strategizing, this knowledge increment can ensure profitable innovation with the help of open innovation platform participants.

Combined with the above research, factors that influence the formal appropriability of the knowledge increment, as affected by the function discussed above, include R&D production input, knowledge production level, and R&D human resources input. Meanwhile, factors that influence the informal appropriability of the knowledge increment include complementary assets, the production function, the knowledge production level, and the input of human resources [2, 8, 30].

On the basis of Romer's knowledge production function [27] and taking into consideration the role of the knowledge increment, a production function of an open innovation platform (referred to below as "platform") and the formal/informal knowledge appropriability of the participants were considered in the research model.

The following basic assumptions were established.

Assumption 1. Knowledge production functions

Based on knowledge production functions, a platform is open and any participant can join. A platform is, in essence, a manager of knowledge production. The platform's knowledge production coefficient is greater than the number of participants: $0 < \delta_2 < \delta_1 < 1$. Complementary resources and advantages exist between a platform and its participants. Heterogeneity in human resources H or knowledge resources K are denoted as $H_1 \neq H_2$ and $K_1 \neq K_2$, and the platform's production function is denoted as $Y_1 = \delta_1 H_1 K_1$. Meanwhile, the participant's knowledge production function is denoted as $Y_2 = \delta_2 H_2 K_2$. Since the form of a platform

is different to the organizational form of a traditional enterprise, different subscripts are used to portray the characteristics of a platform and its participants. After entry onto a platform, both parties perform an initial round of knowledge production according to the knowledge production function. The cooperation knowledge production output is denoted as π , i.e., $\pi = (\delta_1 + \delta_2)(H_1 + H_2)(K_1 + K_2)$.

Assumption 2. Participants' motives

The participants have complementary assets such as intangible resources, capital, and equipment. The appreciation coefficient of complementary assets is ω ($\omega > 1$), and the value of ω is related to the nature of the complementary assets held by the participant. It is assumed that the participants hold complementary assets but lack new knowledge of said complementary assets. The appreciation coefficient ω of the complementary assets can only interact with the knowledge increment ΔK ; the knowledge increment occurs in platform-participant cooperation. The participants may obtain a knowledge increment by entering a platform and helping to revitalize its complementary assets.

Assumption 3. Platform motivation and liquidity policy

The platform devises incentive policies and liquidity policies to attract participants. The participants can distribute the cooperation knowledge production output π obtained from the first round of cooperation. The distribution coefficient of said cooperation knowledge production obtained from the first round in terms of the platform is $0 < \vartheta < 1$ and of the participants is $1 - \vartheta$. Knowledge cooperation also has associated costs, which are influenced by its coefficient c and the existing knowledge K . The knowledge profits of the platform and the participants after the first round of cooperation are $\vartheta\pi - c_1k_2$ and $(1 - \vartheta)\pi - c_2k_1$, respectively. The liquidity policy states that the platform allows the participants to exit after finishing the first round of cooperation for the sake of liquidity.

Assumption 4. Platform knowledge increment strategy

Continued cooperation between both parties produces knowledge increment ΔK after the first round of knowledge cooperation due to differences between these parties. It is assumed that the participants are unable to absorb the knowledge increment as the knowledge is tacit; therefore, the knowledge production capacity of the participants is lower than that of the platform. The platform has two strategies for securing the knowledge increment ΔK by cooperation: the shared knowledge increment and the appropriability knowledge increment. The platform-shared knowledge increment has risks. It is assumed that the platform knowledge sharing risk coefficient is γ , $0 < \gamma < 1$, while the amount of risk is $\gamma\Delta K$. Conversely, there is no risk in the (nonsharing) knowledge appropriability strategy after the first round of cooperation produces the knowledge increment, the platform can choose to share or monopolize, while the participants can also choose to stay on the platform or withdraw from it. Thus, the cooperation between the parties is influenced by the strategy selected by either party.

Assumption 5. Platform leads sharing of knowledge appreciation ΔK

In response to the platform's two treatment strategies for securing the knowledge increment ΔK , i.e., "knowledge appropriability" or "knowledge sharing," the participants also have two strategies, namely, "exiting" or "not exiting." A platform strategy set of $X = \{\text{knowledge appropriability, knowledge sharing}\}$ and participant strategy set $Y = \{\text{exiting, not exiting}\}$ can thus be established: $0 \leq X \leq 1$ and $0 \leq Y \leq 1$. On one side, the game players adjust their own strategies according to the changes in strategies of the other side until a stable status is reached.

Based on the above assumptions, different knowledge production functions can be constructed as follows. The platform and the participants perform knowledge production $T = (\delta_1 + \delta_2)(H_1 + H_2)(\Delta K + K_1 + K_2)$ with knowledge increment cooperation. The platform and the participants cooperate to perform knowledge production $\pi = (\delta_1 + \delta_2)(H_1 + H_2)(K_1 + K_2)$. The platform knowledge production function is $Y_1 = \delta_1 H_1 K_1$. The platform performs production $\Delta Y_1 = \delta_1 H_1 \Delta K$ using the knowledge increment. The knowledge production function of the participants is $Y_2 = \delta_2 H_2 K_2$. The participants perform production $\Delta Y_2 = \delta_2 H_2 \Delta K$ using the knowledge increment. The size of the relationship between the functions is $T > \pi > Y_1 + \Delta Y_1$ and $T > \pi > Y_2 + \Delta Y_2$.

Table 1 lists the correlation coefficients and definitions related to the assumptions given above.

3.2. Research Modeling

3.2.1. Game Strategy Construction. Based on the above assumptions, an asymmetric game relationship was established between the platform and the participants. The effects of the knowledge sharing and knowledge appropriability strategies of the platform on the stability of the system were then analyzed, as outlined below, as participants cooperated or withdrew from the platform according to the evolutionary game theory.

If the platform selects the knowledge appropriability strategy and the participants select the exit strategy, the two distribute the profit of the previous round according to the coefficient and after computing the cooperation cost. Neither party cooperates in this case. The platform selects the appropriability strategy and performs production $Y_1 + \Delta Y_1$ in combination with its own knowledge and using the knowledge increment ΔK . The participants choose to continue in the knowledge production process after exiting the platform based on their own knowledge:

$$\begin{cases} \mu_{11}^{(1)} = \vartheta\pi - c_1K_2 + Y_1 + \Delta Y_1, \\ \mu_{11}^{(2)} = (1 - \vartheta)\pi - c_2K_1 + Y_2. \end{cases} \quad (1)$$

If the platform selects the knowledge appropriability strategy and the participants select the nonexit strategy, the two continue to cooperate after distributing the profit of the previous round according to the coefficient and after computing the cooperation cost. The platform selects the

TABLE 1: Correlation parameters, assumptions, and definitions.

Parameter	Definition
δ_i	Knowledge production coefficient ($0 < \delta_i < 1$, $i = 1, 2$, which represents the platform and the participants)
c_i	Cost coefficient of knowledge cooperation ($0 < c_i < 1$, $i = 1, 2$, which represents the platform and the participants)
H_i	Research and development (R&D) human D ($H_i > 0$, $i = 1, 2$, which represents the platform and the participants)
K_i	Knowledge resources ($K_i > 0$, $i = 1, 2$, which represents the platform and the participants)
ΔK	Knowledge increment of cooperation between both parties ($\Delta K > 0$)
ω	Appreciation coefficient of the complementary assets of participants ($\omega \geq 1$)
ϑ	Distribution coefficient of knowledge production of the first round of cooperation of the platform ($0 < \vartheta < 1$)
γ	Risk coefficient of the knowledge sharing of the platform ($0 < \gamma < 1$)
Y_i	Knowledge production function ($Y_i > 0$, $i = 1, 2$, which represents the platform and the participants)
ΔY_i	Knowledge production output using the knowledge increment ($\Delta Y_i > 0$, $i = 1, 2$, which represents the platform and the participants)
π	Knowledge production output of cooperation between both parties ($\pi > 0$)
T	Knowledge production output of both parties using the knowledge increment ($T > 0$)

knowledge appropriability strategy while the participants do not exit. The platform cooperates with the participants using the knowledge increment ΔK . The platform produces T while generating the cost $c_1 k_2$ of using the knowledge of the other party. The participants choose not to exit and continue cooperating with the platform to continue the knowledge production process. The knowledge production output is π , which generates the knowledge cooperation cost $c_2 k_1$:

$$\begin{cases} \mu_{12}^{(1)} = \vartheta\pi - c_1 K_2 + T - c_1 K_2, \\ \mu_{12}^{(2)} = (1 - \vartheta)\pi - c_2 K_1 + \pi - c_2 K_1. \end{cases} \quad (2)$$

If the platform selects the knowledge-sharing strategy and the participants select the exit strategy, the two no longer continue to cooperate after distributing the profit of the previous round according to the coefficient and after computing the cooperation cost. The platform selects knowledge sharing, but the participants choose to exit and obtain the knowledge increment from the platform. The platform produces $Y_1 + \Delta Y_1$ using the knowledge increment and the risk of sharing $\gamma\Delta K$ is computed. The participants combine the production of the knowledge increment and exert complementary asset leverage to produce $\omega_2(Y_2 + \Delta Y_2)$:

$$\begin{cases} \mu_{21}^{(1)} = \vartheta\pi - c_1 K_2 + Y_1 + \Delta Y_1 - \gamma\Delta K, \\ \mu_{21}^{(2)} = (1 - \vartheta)\pi - c_2 K_1 + \omega_2(Y_2 + \Delta Y_2). \end{cases} \quad (3)$$

If the platform selects the knowledge-sharing strategy and the participants select the nonexit strategy, the two continue to cooperate after distributing the profit of the previous round according to the coefficient and after computing the cooperation cost. The platform selects the knowledge sharing strategy and the participants do not exit; the two parties produce $\omega_2 T$ and a complementary assets leverage effect. The two parties compute their respective costs, $c_1 k_2$ and $c_2 k_1$, and the platform computes the risk of sharing $\gamma\Delta K$:

$$\begin{cases} \mu_{22}^{(1)} = \vartheta\pi - c_1 k_2 + \omega_2 T - c_1 K_2 - \gamma\Delta K, \\ \mu_{22}^{(2)} = (1 - \vartheta)\pi - c_2 K_1 + \omega_2 T - c_2 K_1. \end{cases} \quad (4)$$

Based on the evolutionary game analyses in the above four cases, a payoff matrix of both parties, i.e., the platform and the participants, was drawn, as given in Table 2.

3.2.2. Model Solving and Impact Analysis. The evolutionary game model was solved and an analysis of its impact was conducted as follows. According to the assumptions given above, the problem of a random-matching game playing between groups 1 and 2 was considered. In terms of platform (1), it was assumed that the proportion of knowledge appropriability strategy selection was x and that the proportion of knowledge-sharing strategy selection was $(1 - x)$. Meanwhile, as regards participants (2), the proportion of exit strategy selection was assumed to be y , and the proportion of nonexit strategy selection was assumed to be $(1 - y)$. x and y are the functions with respect to time t . According to the evolutionary game theory [31], the replicator dynamics equations of both parties according to their respective strategy selections are

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x(1-x)[y(\mu_{11}^{(1)} - \mu_{21}^{(1)}) + (1-y)(\mu_{12}^{(1)} - \mu_{22}^{(1)})], \\ F(y) &= \frac{dy}{dt} = y(1-y)[x(\mu_{11}^{(2)} - \mu_{12}^{(2)}) + (1-x)(\mu_{21}^{(2)} - \mu_{22}^{(2)})]. \end{aligned} \quad (5)$$

Let $dx/dt = 0$; $dy/dt = 0$ has five dynamic system equilibrium points in the plane $R = \{(x, y) | 0 \leq x \leq 1, 0 \leq y \leq 1\}$: $(0, 0)$, $(0, 1)$, $(1, 0)$, $(1, 1)$, and (x_1^*, y_1^*) , where

$$\begin{aligned} x_1^* &= \frac{\mu_{21}^{(2)} - \mu_{22}^{(2)}}{(\mu_{21}^{(2)} - \mu_{22}^{(2)}) - (\mu_{11}^{(2)} - \mu_{12}^{(2)})}, \\ y_1^* &= \frac{\mu_{12}^{(1)} - \mu_{22}^{(1)}}{(\mu_{12}^{(1)} - \mu_{22}^{(1)}) - (\mu_{11}^{(1)} - \mu_{21}^{(1)})}. \end{aligned} \quad (6)$$

TABLE 2: Payoff matrix of players.

		Participants	
		Exit: y	Nonexit: $1 - y$
Open innovation platform	Knowledge appropriability: x	$\mu_{11}^{(1)}; \mu_{11}^{(2)}$	$\mu_{12}^{(1)}; \mu_{12}^{(2)}$
	Knowledge sharing: $1 - x$	$\mu_{12}^{(1)}; \mu_{12}^{(2)}$	$\mu_{22}^{(1)}; \mu_{22}^{(2)}$

The Jacobian matrices of equations $F(x)$ and $F(y)$ are

$$J = \begin{bmatrix} (1 - 2x)\{\mu_{12}^{(1)} - \mu_{22}^{(1)} - [(\mu_{12}^{(1)} - \mu_{22}^{(1)}) - (\mu_{11}^{(1)} - \mu_{21}^{(1)})]y\} & -x(1 - x)[(\mu_{12}^{(1)} - \mu_{22}^{(1)}) - (\mu_{11}^{(1)} - \mu_{21}^{(1)})] \\ -y(1 - y)(\mu_{21}^{(2)} - \mu_{22}^{(2)}) - (\mu_{11}^{(2)} - \mu_{21}^{(2)}) & (1 - 2y)\{\mu_{21}^{(2)} - \mu_{22}^{(2)} - [(\mu_{21}^{(2)} - \mu_{22}^{(2)}) - (\mu_{22}^{(2)} - \mu_{12}^{(2)})]y\}. \end{bmatrix} \quad (7)$$

Based on the local stability judgement method of the Jacobian matrices [32], we can determine whether the specific strategy is an evolutionary stability strategy (ESS) according to the value of the determinant of the Jacobian matrix. Table 3 shows the determinant and the traces of the matrix J .

The random-matching game problem between platform (1) and participants (2) can be considered based on the given assumptions. Five dynamic equilibrium points can be obtained: $(0, 0)$, $(0, 1)$, $(1, 0)$, $(1, 1)$, and (x^*, y^*) . According to the local stability of the Jacobian matrix, a local stability analysis was conducted on the four system equilibrium points. It was found that the values of the determinants and traces of each point were associated with ω , ΔK , γ , π , and T , referring to the system equilibrium points of the platform and the participants playing the game in different scenarios, as well as the local stability analyses.

The ESS finally obtained in the evolutionary game is a proportion, and such a proportion will show after a period of time. The ESS process of finding a strategy uses the fitness function to find the average fitness (i.e., group average payment) and then multiplies the difference between this fitness and a certain strategy payment by the strategy probability to obtain the replicator dynamics equations of the specific strategy growth rate. In order to analyze the direction of evolution, we used the concept of saddle point. The saddle point is expressed as a singular point that is stable in one direction in the differential equation and unstable in the other direction.

The ESS in different scenarios, as well as the local stability analyses based on the saddle point, is shown in Table 4.

The conclusions are as follows.

Conclusion 1. When $\omega = 1$ (condition 1), $(1, 0)$ is the instable point, while $(0, 0)$, $(0, 1)$, and $(1, 1)$ are the saddle points; (x^*, y^*) is not the equilibrium point.

Conclusion 2. When $1 < \omega < (\pi + \Delta K\gamma/2T) + 1$ (condition 2), $(1, 0)$ is the ESS point, $(0, 0)$ is the unstable point, and $(0, 1)$, $(1, 1)$, and (x^*, y^*) are the saddle points.

Conclusion 3. When $\omega > (\pi + \Delta K\gamma/2T) + 1$ (condition 3), $(0, 0)$ and $(1, 0)$ are the ESS points and $(0, 1)$, $(1, 1)$, and (x^*, y^*) are the saddle points.

The above three different conditions correspond to the following system trajectory chart (Figure 1).

3.3. Numerical Simulation. MATLAB R2018a programming was further utilized in this study to verify the correctness of the evolutionary game model via numerical simulation. The path of evolution of the strategies of the platform and the participants in the disequilibrium state were visualized and the critical parameters were investigated. It was assumed that (x_0, y_0) is the original proportion of the knowledge appropriability and exit strategies selected by platform (1) and participants (2). The effects from changes in the critical parameters on the path of evolution of the system were as follows.

3.3.1. Parameter Analysis. To observe the effects of ω on the system by means of simulation, an initial value was assigned to the system parameters (Table 5).

Considering the reality that an open innovation platform improves an enterprise's innovation ability by relying on an external force [33], the platform is generally small and contains micro-organizations supported by external experts. Therefore, the initial value of the core R&D personnel of the platform was defined herein as $H_1 = 20$.

Among different stages of the platform growth process, the diversity of participants in the initial stage of the platform is relatively narrow. In the development and maturation stages, the participants become diversified [34] and can thus be generalized.

An organizational scale equivalent to the scale of the core R&D human resources of the platform in the initial stage was selected here, i.e., $H_2 = 30$. The knowledge production coefficient was set according to the assumptions given above. It was assumed that the knowledge production coefficient of the platform was greater than that of the participants, i.e., $\delta_1 = 0.7$ and $\delta_2 = 0.2$, respectively. To maintain generality, the quantity of the knowledge resources of both parties was minimized: $K_1 = 15$ and $K_2 = 10$ for the platform and the participants, respectively. The profit distribution coefficient ϑ was set so that the ratio of the proportions of the platform and the participants was 0.4:0.6. The cooperation cost coefficients of the two, c_1 and c_2 , were set according to the assumed cooperation cost of the platform being

TABLE 3: Expressions of the matrix determinants and traces of stable points.

Stable points	Matrix determinant and trace expressions	
(0, 0)	detJ	$(\pi - T\omega)[T(1 - \omega) + \Delta K\gamma]$
	trJ	$T(1 - 2\omega) + \Delta K\gamma + \pi$
(0, 1)	detJ	$-\Delta K\gamma(\pi - T\omega)$
	trJ	$\pi - \Delta K\gamma - T\omega$
(1, 0)	detJ	$[T(1 - \omega) + \Delta K\gamma][\Delta Y_2\omega + Y_2(\omega - 1)]$
	trJ	$T(1 - \omega) + Y_2(\omega - 1) + \Delta K\gamma + \omega\Delta Y_2$
(1, 1)	detJ	$-\Delta K\gamma[\Delta Y_2\omega + Y_2(\omega - 1)]$
	trJ	$\Delta Y_2\omega - \Delta K\gamma + Y_2(\omega - 1)$
(x^*, y^*)	detJ	$-(\Delta K\gamma(\pi - T\omega)[T(1 - \omega) + \Delta K\gamma]/T(\omega - 1))$
	trJ	$((-\Delta K^2\gamma^2 + \Delta K\gamma T(\omega - 1) + T^2\omega(1 - \omega) + \pi T(\omega - 1))/T(\omega - 1))$

TABLE 4: Equilibrium point of equilibrium-type systems and local stability analyses.

Point	Condition 1		Result	Condition 2		Result	Condition 3		Result
	detJ	trJ		detJ	trJ		detJ	trJ	
(0, 0)	-	-	Saddle point	-	-	Unstable	+	-	ESS
(0, 1)	-	-	Saddle point	-	+	Saddle point	-	-	Saddle point
(1, 0)	+	+	Unstable	+	-	ESS	+	-	ESS
(1, 1)	-	-	Saddle point	-	-	Saddle point	-	-	Saddle point
(x^*, y^*)	Not equilibrium point			-	-	Saddle point	-	-	Saddle point

ESS: evolutionary stability strategy.

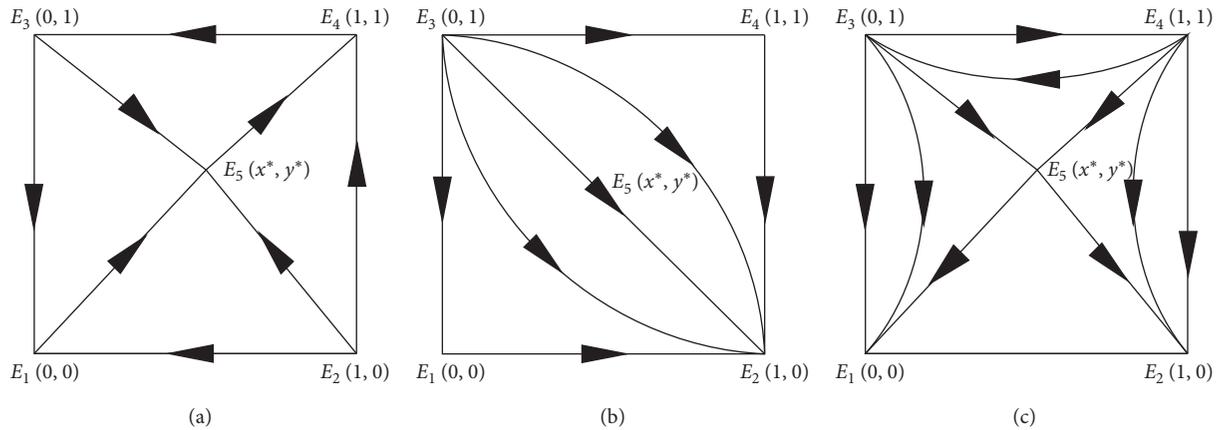


FIGURE 1: Dynamic evolution of the strategies under different conditions.

TABLE 5: Assigning values to the system parameters.

Parameters	δ_1	δ_2	H_1	H_2	K_1	K_2	ϑ	c_1	c_2	ΔK	γ
Value assigned	0.7	0.2	20	30	15	10	0.4	0.1	0.15	5	0.2

TABLE 6: Value of parameter ω .

Parameter	ω
Condition 1	1
Condition 2	1.2
Condition 3	1.3

lower than that of the participants, i.e., 0.1 and 0.15, respectively. To maintain generality, the knowledge increment obtained by cooperation was set to a relative value, i.e., $\Delta K = 5$, and the initial value of the risk coefficient of the platform's knowledge sharing strategy was set to $\gamma = 0.2$.

(1) *The Appreciation Coefficient of Complementary Assets ω .* Three different scenarios of system equilibrium conditions were analyzed. The values of the appreciation coefficient of

complementary assets ω were set according to the three evolution stability cases presented below (Table 6), which represent the different states of ω .

To observe the proportion and the path of evolution of the game groups, the initial proportions of the platform and the participants were set to $x_0 = 0.5$ and $y_0 = 0.5$, respectively. The simulation results are shown in Figure 2.

Figure 2 shows that ω evolves differently as the system increases in size within the given range toward three strategy

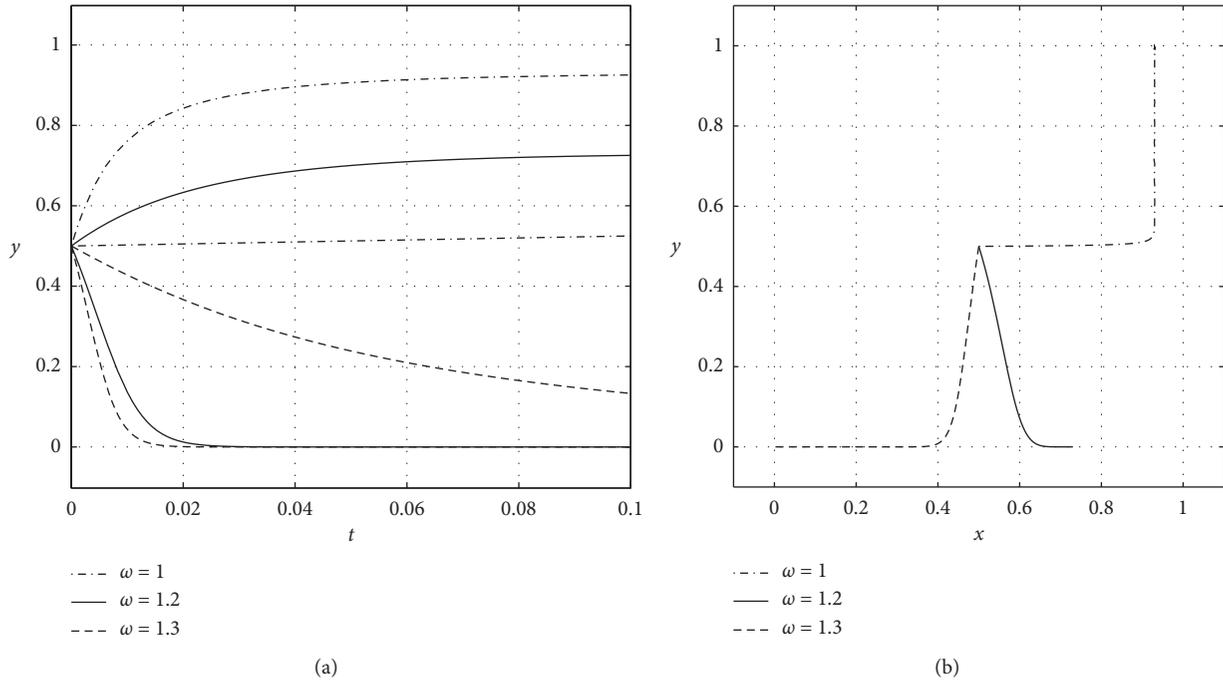


FIGURE 2: Effects of ω on the system stability strategies.

points: (1, 1), (1, 0), and (0, 0), i.e., knowledge appropriability/exit, knowledge appropriability/no exit, and knowledge sharing/no exit.

(2) *Knowledge Increment of Cooperation ΔK* . The key point versus the stability point was next set to $E(1, 0)$ (condition 2, $\omega = 1.2$). The effects of the knowledge increment ΔK of cooperation between both parties, in this case, are shown in Figure 3.

In this case, different ΔK values primarily affected the initial proportion and the strategy of the participants y . When ΔK was 10 and 100, the participants evolved toward the “no exit” strategy; when ΔK was 10,000, the participants evolved toward the “exit” strategy.

(3) *Knowledge Production Output on Knowledge Increment ΔY_2* . The practical significance of ΔY_2 is that the participants use the knowledge increment ΔK shared by the platform for their own reproduction. The effects of ΔY_2 were analyzed with the strategy stability point $E(1, 0)$ (condition 2, $\omega = 1.2$) (Figure 4).

Various combinations of the strategies of the platform and the participants were formed (knowledge appropriability/no exit). As shown in Figure 4, when $\Delta Y_2 = 10,000$, the platform tended to perform knowledge sharing; when the value of ΔY_2 was smaller, i.e., $\Delta Y_2 = 10$, the platform was still inclined toward sharing. The participants tended not to exit, regardless of changes in ΔY_2 , which indicates that ΔY_2 primarily impacts the choice of knowledge strategy. ΔY_2 is a composite variable based on ΔK . The superposition of the knowledge production function causes the role of ΔY_2 to differ from the role of the knowledge increment as discussed above.

(4) *Knowledge Production Output π* . The knowledge production output of platform-participant cooperation was generated based on the knowledge production coefficient δ_i , human resources H_i , and knowledge stock K_i of both parties. The effects of π on the system strategy were analyzed by the $E(1, 0)$ point (condition 2, $\omega = 1.2$) (Figure 5).

As shown in Figure 5, when π was 10 or 100, the platform evolved toward knowledge sharing; meanwhile, when $\pi = 10,000$, it evolved toward knowledge appropriability. This indicates that the knowledge production output π of cooperation between both parties affects the choice in strategy of the platform, while the participants do not exit, regardless of the value of π .

(5) *Knowledge Production Output T* . Knowledge production output T refers to the output of knowledge produced by both parties using the knowledge increment, and the effects of which were explored based on three different conditions (Figure 6).

As shown in Figure 6, all T values affected the choice of strategy of the platform. T increased as the platform strategy changed from knowledge sharing to knowledge appropriability, which suggests that the knowledge production output T of both parties using the knowledge increment has critical points. T influences the platform’s selection of strategy, thus influencing the direction of the system’s evolution. Figure 6 shows the effects of T on the point $E(1, 0)$ (condition 2, $\omega = 1.2$).

(6) *Amount of Knowledge Produced Y_2* . Amount of knowledge produced Y_2 refers to the output of the participants of innovation cooperation in the knowledge production process. The simulation results of Y_2 are shown in Figure 7.

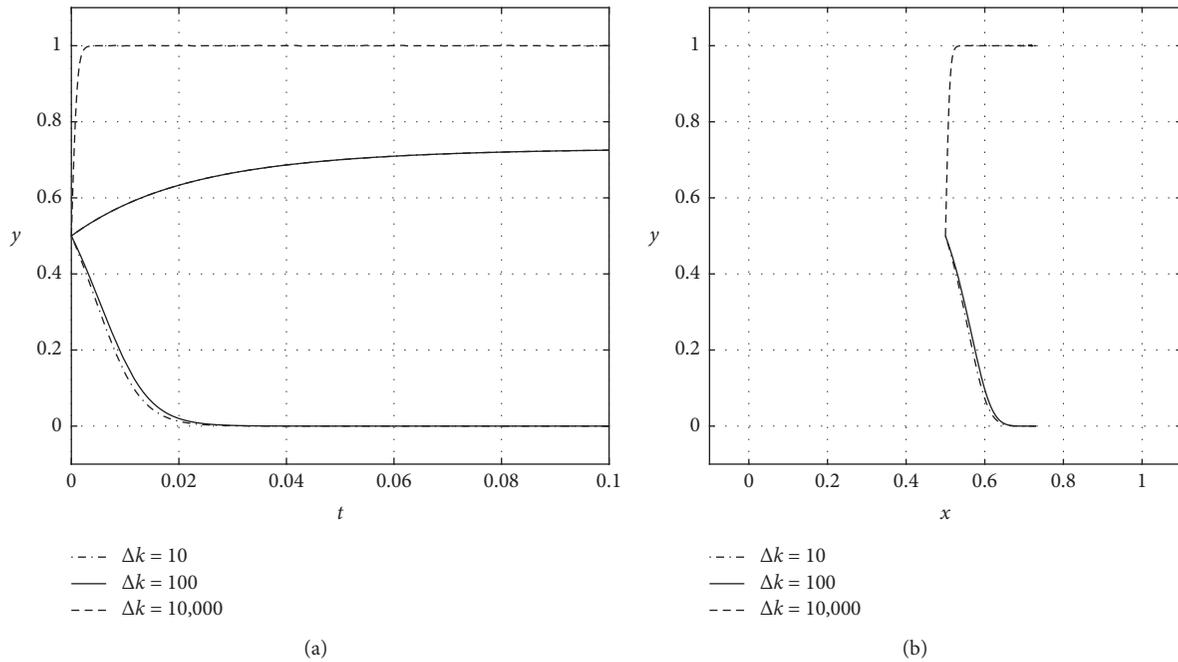


FIGURE 3: Effects of ΔK on system strategy $E(1,0)$.

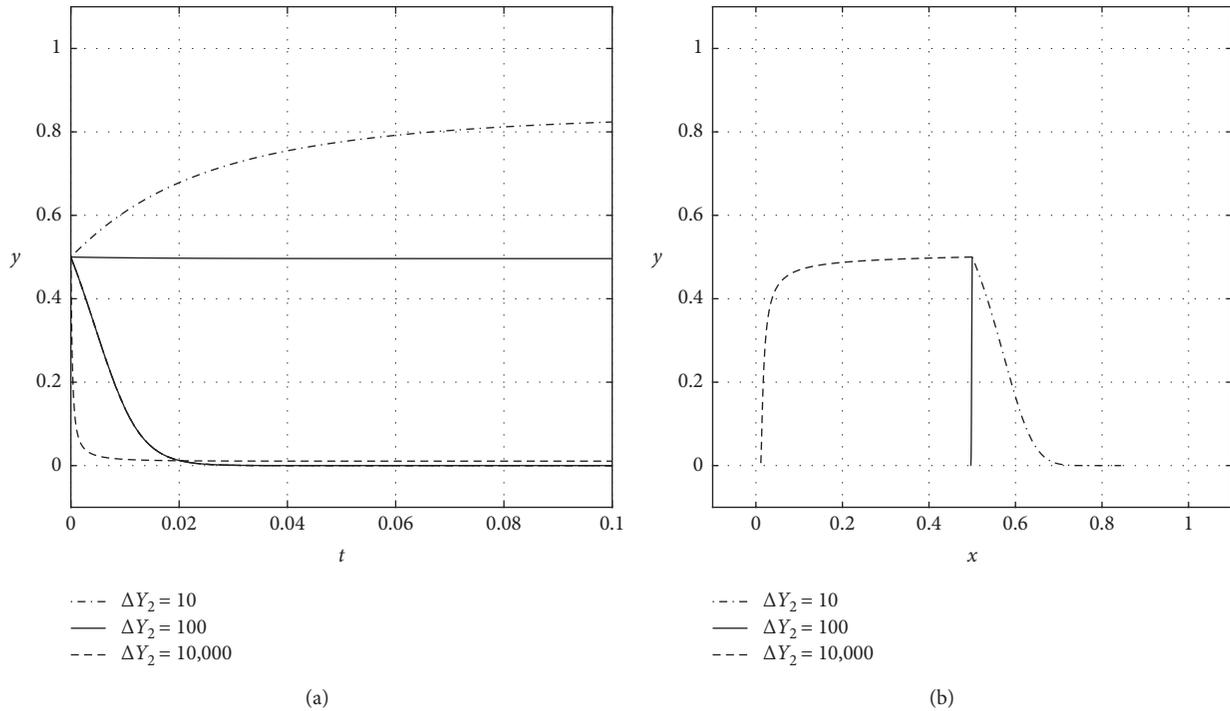


FIGURE 4: Effects of ΔY_2 on system strategy $E(1,0)$.

As shown in Figure 7, when the system has two ESS points (condition 3, $\omega = 1.3$), the system evolves toward the $E(0,0)$ point to form a knowledge-sharing/no exit strategy regardless of changes in Y_2 . This indicates that an increase in Y_2 accelerates the knowledge sharing of the platform.

(7) *Other System Parameters.* Other system parameters include the platform's knowledge-sharing risk coefficient γ , the cooperation cost coefficient of both parties c_i , and the knowledge production distribution coefficient ϑ . The simulation results show that when there was no equilibrium

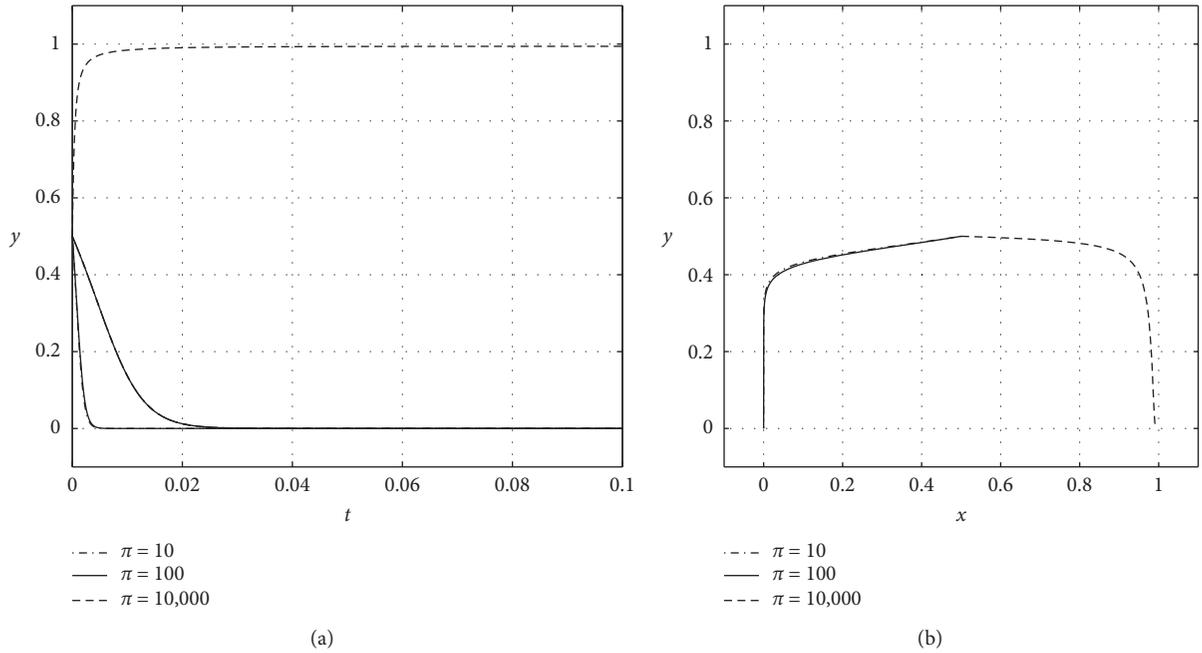


FIGURE 5: Effects of π on system strategy $E(1,0)$.

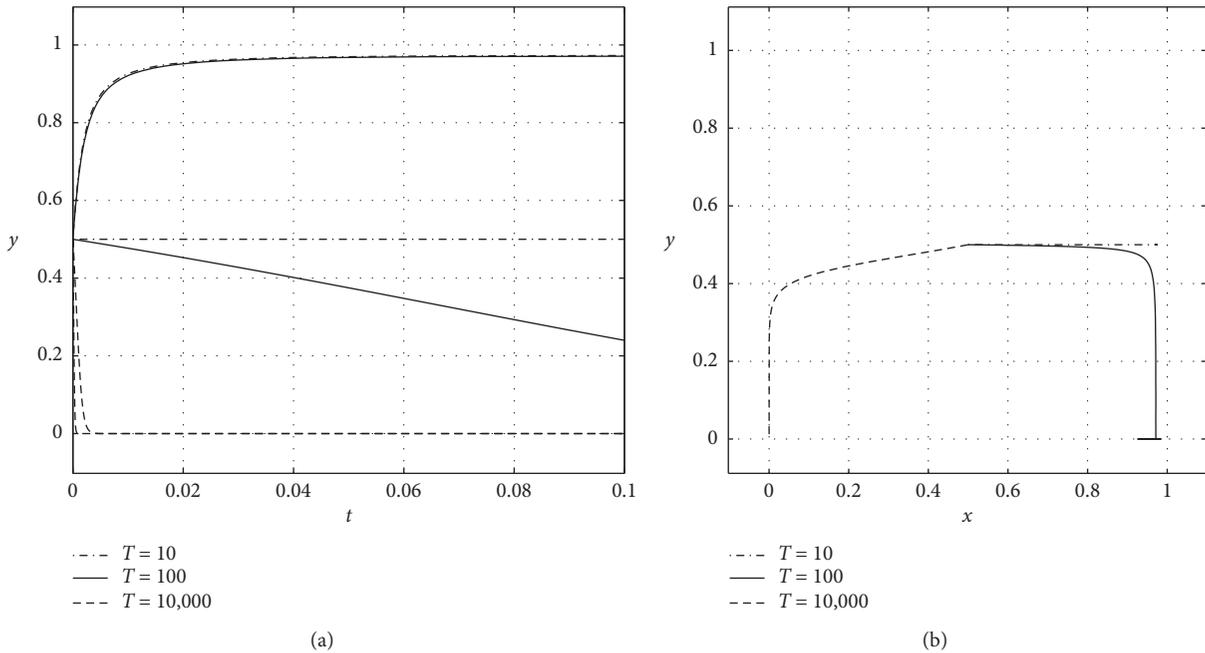


FIGURE 6: Effects of T on system strategy $E(1,0)$.

point (condition 1, $\omega = 1$), the parameter γ affected the path but did not influence the evolution, which is similar to Y_2 . The other parameters showed no effects on the evolution of the strategy or the path of evolution of the system.

3.3.2. *Summary of the Impact of the Parameters.* Table 7 summarizes the effects of the parameters analyzed on the stability of cooperation, as well as the degree of knowledge

sharing. As the appreciation coefficient of complementary assets ω increased, stability of cooperation was achieved and the effects of knowledge sharing were improved in this case. The knowledge increment ΔK had a negative impact on the stability of cooperation because it drove the participants to exit from the platform. The increase in the ΔY_2 and Y_2 parameters had no effect on the stability of cooperation, but played a positive role in the degree of knowledge sharing.

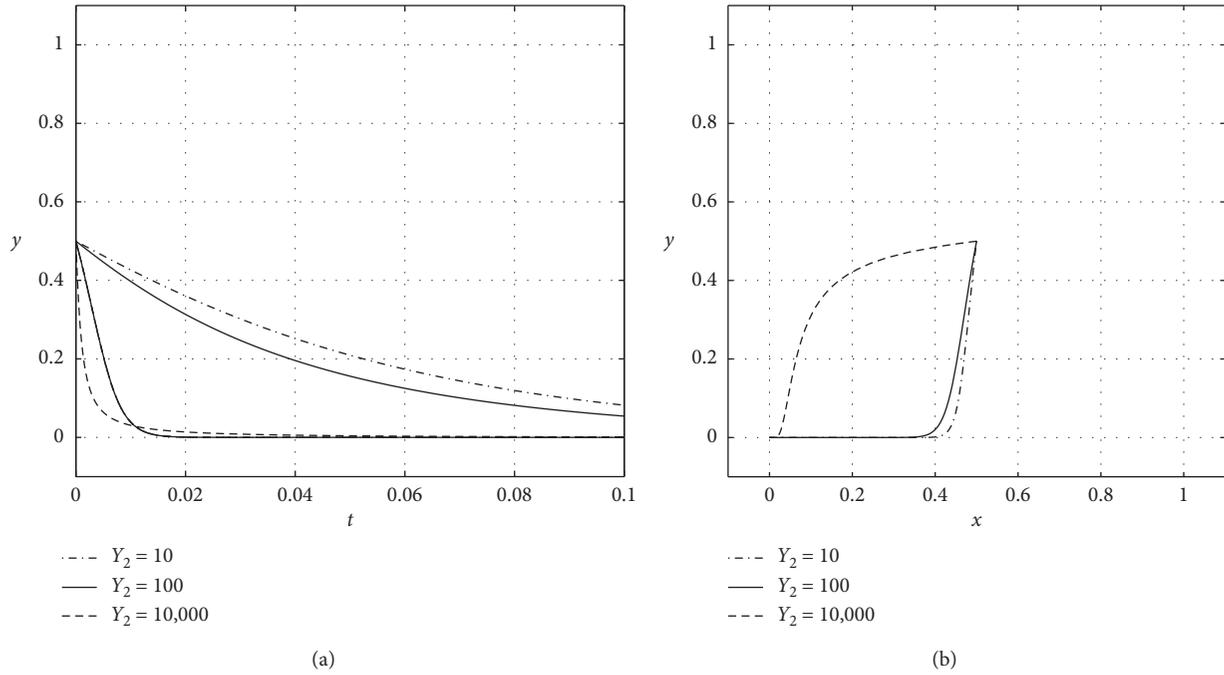
FIGURE 7: Effects of Y_2 on condition 3.

TABLE 7: Summary of the roles of the parameters.

Parameters	Degree of stability of cooperation	Degree of knowledge sharing
ω	Positive	Positive
ΔK	Negative	No
ΔY_2	No	Positive
Y_2	No	Positive
π	No	Negative
T	No	Negative
Y_2	No	Positive

Note: "Positive" and "negative" labels refer to the positive/negative impact brought about by an increase in the parameters, "no" label refers to no impact brought about by an increase in the parameters.

Increases in the parameters π and T had no effect on the stability of cooperation and exerted a negative impact on the degree of knowledge sharing.

4. Discussion

The results of the numerical simulation are explained and discussed in depth in this section:

- (1) The simulation showed that a smaller ω brought the proportions of both parties closer to (1, 1), although the knowledge appropriability/exit strategy combination was not the original intention of the platform or the participants. This indicates that the parameter ω has a leverage effect. The roles of complementary assets in innovation have always been discussed but remain inconclusive. The results of this study usefully revealed that complementary assets are a very critical and sensitive variable in open innovation cooperation.

- (2) In simulating other cases (condition 1, $\omega = 1$; condition 3, $\omega = 1.3$), it was found that the knowledge increment ΔK only influenced the direction of evolution of the strategy of the participants. Under all circumstances, an increase in ΔK caused a tendency for the participants to withdraw from the platform. In other words, the generated knowledge increment has an important impact on the stability of cooperation.
- (3) The evolutionary game analysis conducted in this study showed that the participants tended to exit from the platform and perform independently when ω decreased and ΔK increased. In this case, relevant influencing parameters can be very critical, and further analysis of the mechanism may be required.

The limitations of this research are as follows. First, forms of complementary assets, excluding capital (such as currency), also define and quantify the size of influencing coefficients, which was neglected here. Second, the

knowledge production function was composed of different variables, making it possible only to depict abstract relationships between the parameters. Third, the effects of certain parameters were defined on the basis of cooperation, but the preconditioned variables that influence the establishment of cooperation were not considered.

5. Conclusions

A composite production process was examined wherein the human resources, material resources, and amount of knowledge produced by an open innovation platform and its participants affected the knowledge that is cooperatively produced. Analysis of the unstable, limiting factors revealed various effects of the critical variables on different strategy points of the system. These results were used to determine the complex mechanisms of cooperative knowledge production between an open innovation platform and its participants.

The conclusions of this study can be summarized as follows:

- (1) The strategic points of the appropriability/no exit combination formed in the evolutionary game have an important influence on the cooperative relationship between an open innovation platform and its participants. This not only enables the open innovation platform to retain participants but also increases the knowledge-based profit of its operations, which is of great significance for said platform to inform its platform operation management and knowledge strategy selection in reality.
- (2) Among the many parameters of the system between an open innovation platform and its participants, the appreciation coefficient of complementary assets ω is a key parameter that affects the evolution of the strategy of the system, ensuring that said platform and its participants present different evolutionary strategies.
- (3) The knowledge production output ΔY_2 of participants also affects the relationship between an open innovation platform and said participants, which also needs to be considered in reality. An increase in ΔY_2 promotes the open innovation platform to adopt a knowledge-sharing strategy.

Management suggestions in light of the research conclusions are as follows. First, participants may also prejudge their future cooperation strategy by analyzing the appreciation coefficient of complementary assets, the knowledge increment possibly generated by cooperation, and other factors. Second, open innovation platforms with different strategic orientations can choose the most consistent strategies. For platforms dominated by a high return and a high profit (such as purely commercial platforms), the equilibrium points of the knowledge-appropriability/no exit strategy can be prioritized. For platforms that seek stability of cooperation and profit (such as general commercial platforms, incubation platforms, and governmental

platforms), the knowledge-sharing/no exit or knowledge-appropriability/no exit equilibrium points should be prioritized. Such strategies both have profitability and share ability, thus maintaining the platform's profits as well as social benefits.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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